The Meteorological Magazine

December 1991

Indian Ocean circulation model
Meteorological products for agriculture
July 1959 temperatures

Met.O.998 Vol. 120 No. 1433

551.465(267)

An Ocean General Circulation Model of the Indian Ocean for hindcasting studies

D.J. Carrington
Meteorological Office, Bracknell

Summary

As part of the WMO TOGA (Tropical Oceans Global Atmosphere) programme, an Ocean General Circulation Model of the Indian Ocean has been developed at the Meteorological Office with the aim of being able to hindcast the upper-level circulation. In this paper the background to this project is outlined, including an overview of the important processes in tropical ocean dynamics and the main features of the Indian Ocean circulation. A description of the model is then given, and the model simulation of the climatological seasonal cycle currents in response to climatological wind stresses and heat fluxes is discussed. In a subsequent paper the response of the model to interannually varying forcing fields (a further step towards developing the hindcasting capability of the model) will be discussed.

1. Introduction

In the early 1980s, the World Climate Research Programme of the World Meteorological Organization inaugurated an international co-ordinated programme of research, called TOGA (Tropical Oceans Global Atmosphere) to run from 1985 to 1995. It is designed to investigate the interactions between the tropical oceans and the atmosphere with a view to furthering the understanding of this coupled system and ultimately to forecast its changes (WCRP 1985).

TOGA consists of two main streams of research: observational and modelling. The principal aim of the modelling programme is to produce a realistic fully coupled operational model of the tropical oceans and global atmosphere. The achievement of this objective is necessarily a step-by-step process — each of the tropical oceans is studied separately, and a hierarchy of models is used to explore the physical processes involved.

One of the contributions being made to this research by the Meteorological Office Unit at the Hooke Institute in Oxford is the development of an Ocean General Circulation Model (OGCM) of the Indian Ocean for hindcasting the upper-level circulation. In this paper a description of the model is given and an assessment made of its ability to simulate the climatological currents in the Indian Ocean in response to climatological forcing. In a subsequent paper the next step in developing the hindcasting capability of the model, namely the use of fields derived from operational Numerical Weather Prediction model analyses to force the model, will be discussed.

Before proceeding to the description of the model in section 3, an introduction to the subject of modelling the Indian Ocean is given in section 2. The important aspects of tropical ocean dynamics are outlined, leading to an overview of the Indian Ocean circulation; a summary of the modelling work relevant to this study is then given. This section provides the background for both this paper and the subsequent paper in which further results are presented.

2. Background to Indian Ocean modelling

2.1 Tropical ocean dynamics

Overviews of ocean circulation in the Tropics have been provided by Hastenrath (1985) and Knox and Anderson (1985). The principal driving force for surface

currents in the Tropics is the wind stress. Since the TOGA programme is concerned with tropical ocean to global atmosphere interaction, the currents which are of greatest interest are those which have the maximum impact on low latitude sea surface temperatures, namely the wind-driven surface currents of the tropical regions. The World Ocean Circulation Experiment (WOCE) will seek further understanding of the circulation in the global ocean, both in the surface layers and at depth.

The wind drives the ocean both directly and indirectly. Because of the Coriolis force the direct forcing results in Ekman drift, by which wind-driven currents flow to the right of the wind direction in the northern hemisphere and to the left in the southern hemisphere. In the Tropics, two differences with respect to circulation in higher latitudes arise. Firstly, the Coriolis parameter on the Equator is zero so that the current direction there tends to be directly downwind. Secondly, the reversal in direction of the Ekman drift relative to the wind direction across the Equator results in divergent flow away from the Equator if the wind is easterly, convergent if westerly; divergence leads to upwelling on the Equator, convergence to downwelling. The zero value of the Coriolis parameter on the Equator enables equatorial currents to be spun-up rapidly; for example, a zonal wind stress of 0.2 dyn cm^{-2} acting for 1 month over a depth of 50 m will produce a current speed of about 1 m s^{-1}.

The wind affects currents indirectly in two ways. Firstly, the curl of the wind stress produces vertical motion in the oceanic boundary layer (so-called 'Ekman pumping'); this leads to vertical displacement of the thermocline, resulting in horizontal density gradients which in turn produce geostrophic currents. Secondly, changes in the wind forcing can generate waves in the surface currents. These waves provide a key mechanism by which information can be transmitted rapidly within the tropical oceans. The equatorial region forms a wave-guide for zonally-propagating waves, enabling information to be carried across a tropical ocean far more rapidly than at mid latitudes. Rossby waves are the principal mode for westward-propagating waves and Kelvin and Yanai (mixed Rossby-gravity) waves for eastward-propagating disturbances.

Because the applied wind stress on an ocean is a time-variant property, wind-driven currents vary correspondingly. On the inter-seasonal time-scale, the wind patterns in the tropical Pacific and Atlantic remain fairly constant and nowhere are there large-scale seasonal reversals in wind direction. However, in many parts of the Indian Ocean the wind direction does reverse seasonally (see Fig. 1). This factor (together with the distinctly different geography of the Indian Ocean in comparison with that of the Pacific and Atlantic, the Indian Ocean having a northern land boundary at sub-tropical latitudes) results in the principal currents being significantly different from those in the other two oceans, especially in the equatorial and north Indian Ocean.

2.2 Indian Ocean circulation

2.2.1 Equatorial currents

During the winter monsoon (or North-east Monsoon), an eastward Equatorial Counter Current (ECC) lies between the two westward currents — the North Equatorial Current (NEC) and South Equatorial Current (SEC) — driven by the Trade Winds. In contrast to the Pacific and Atlantic, the ECC lies to the south of the Equator, at about 5°S; this is consistent with the applied wind field in Fig. 1(a).

During the summer monsoon (or South-west Monsoon), the NEC and ECC disappear and are replaced by a single eastward current, the South-west Monsoon Current (SMC). The boundary between the SMC and the SEC lies close to the Equator.

The transition periods between the monsoons tend to be characterized by a rather more variable current pattern; the SEC is the only main current which persists though all the seasons, though its latitudinal position varies. A strong (up to 1 m s^{-1}) eastward current, the Wyrtki Jet (Wyrtki 1973), has been observed (Knox 1976) to develop on the Equator during both transition periods as a result of strong westerly winds.

The principal sub-surface current is the Equatorial Undercurrent (EUC) which exhibits a strong semi-annual cycle. It is effectively wind forced, being created by the sub-surface longitudinal pressure gradients which result from the surface wind-driven flow. It flows westward during the transition periods between the monsoons and eastward the rest of the year. This is in contrast to the EUC in the Pacific and Atlantic which flows eastward thoughout the year in response to the sub-surface zonal density gradient along the Equator, formed mainly by the westward surface flow. In the Indian Ocean the behaviour of the EUC seems to be more complex and is not a simple function of the equatorial winds.

2.2.2 Western boundary

The western boundary current of the Indian Ocean is unique amongst the major western boundary currents of the world in that it exhibits complete reversal in direction in an annual cycle (with the exception of the boundary current in the western Pacific which also undergoes a seasonal reversal, though of smaller amplitude, in response to the reversal in the monsoon winds). During the North-east Monsoon, the surface current is southward along most of the length of Africa, including a strong cross-equatorial flow. Between about April and May the flow everywhere northward of about 10°S reverses direction; the cross-equatorial flow becomes northward and a major boundary current, the Somali Current, is generated. A component of the SEC turns northward to form the cross-equatorial flow, the remainder turning southward as during the North-east Monsoon.
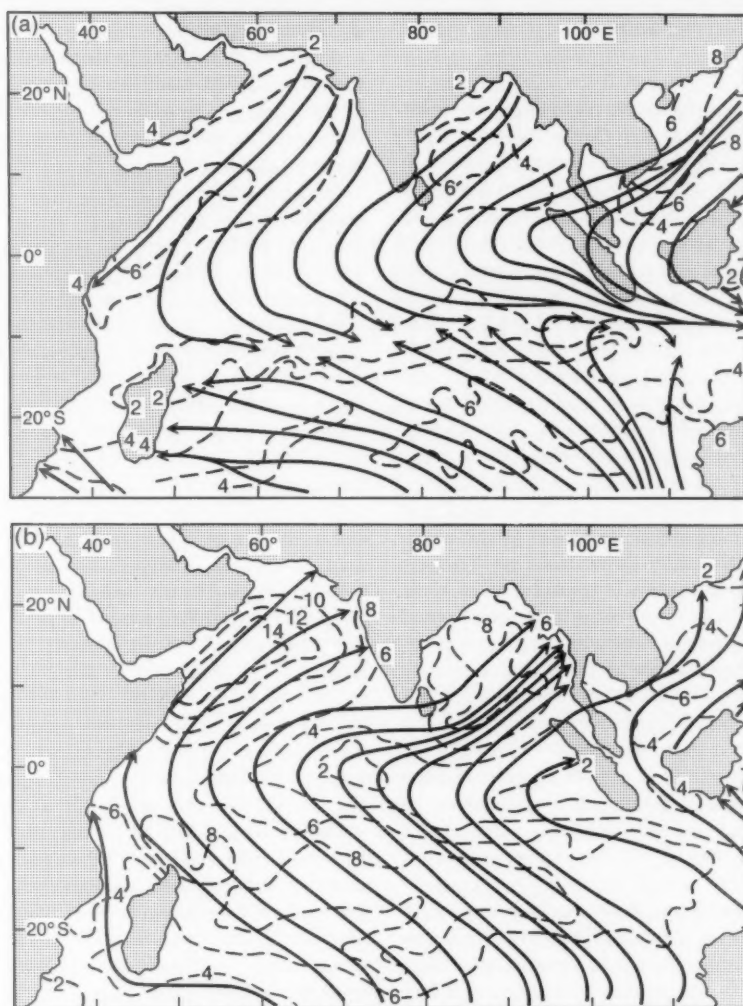
Figure 1. Surface wind field over the tropical Indian Ocean in (a) January and (b) July; streamlines, and isotachs (m s^{-1}). (From Hastenrath and Lamb, 1980).

In association with the Somali Current, a major recirculation pattern develops. The flow separates from the coast at approximately 9–10° N and forms a large gyre, the 'Great Whirl' (first recorded by Findlay (1866)). A second, smaller, recirculation pattern has also been detected offshore between about 10° N and 12° N, the 'Socotra Eddy'. These current systems appear to be a complex result of both remote and local forcing (Lighthill 1969, Leetmaa 1973) and may have a natural time-dependence rather than being a steady-state pattern (McCreary and Kundu 1988).

2.2.3 Interannual variability

It is well known that the monsoon winds, and the rainfall on the Indian sub-continent associated with the summer monsoon, vary from year to year. Far less is known about the interannual variability in the ocean

currents which must result. Most of the earlier work carried out on the link between the Indian Ocean and the monsoon has concentrated on the sea surface temperatures (SSTs) in the Arabian Sea. Schott and Quadfasel (1982) observed large interannual differences in the currents in the Somali region during the onset of the South-west Monsoon, and there is a correlation between low SSTs in the Arabian Sea, a wet monsoon in India and a strong two-gyre system in the Somali region. The need for greater understanding of the interannual variability in the Indian Ocean as a whole has been stressed by Knox and Anderson (1985).

A model of the Indian Ocean which seems to simulate well the climatologically observed currents in response to forcing by climatological winds should provide a suitable tool for studying this interannual variability when forced by interannually varying winds.

2.3 Indian Ocean modelling

2.3.1 General

Lighthill (1969) was the first to try to model the wind-driven circulation of the Indian Ocean. Wunsch (1977) later investigated the response of a model to a seasonally varying wind-forcing. Climatological winds have subsequently been used as forcing in a hierarchy of model types; for example, Schott *et al.* (1988) used both a reduced-gravity model and a multi-layer model forced by the climatological winds of Hellerman and Rosenstein (1983). Many limited-area modelling studies have been carried out, with particular interest being paid to the Somali region; McCreary and Kundu (1988), for example, used an idealized wind stress pattern and a so-called 2½-layer model to produce a two-gyre system.

Only recently has much work been done using observed winds for forcing a model. Luther and O'Brien (1989) used the ship-wind data set of Cadet and Diehl (1984) to force a reduced-gravity model of the whole Indian Ocean. The simulated currents are qualitatively realistic; the two-gyre system is reproduced in some years and not in others, a feature of interannual variability which is in agreement with observations.

In order to simulate the temperature field accurately the thermodynamics as well as the dynamics of the model upper levels must be represented realistically and vertical heat transport must be included. Therefore the forcing by observed winds of a more complex model, which represents the 3-dimensional circulation, is required.

2.3.2 OGCMs

Bryan (1969) was the first to develop a general circulation model of the ocean (an OGCM), which was later adapted by Semtner (1974) and then by Cox (1984). The use of OGCMs has been explored extensively, including their response to observed forcing. Thus, Philander and Seigel (1985) clearly demonstrated the ability of such models to reproduce the observed variations of thermal and velocity structure of equatorial oceans in response to NWP model winds, and since then, study of the tropical Pacific Ocean using OGCMs forced by actual winds has become relatively well advanced. Leetmaa and Ji (1988) used wind stresses both from ship reports and from operational atmospheric analyses when assimilating hydrographic and thermal data and estimates of sea surface temperatures derived from satellite radiances and ship observations into the National Meteorological Centre's OGCM for operational hindcasting of the tropical Pacific. Harrison *et al.* (1989) have further indicated the sensitivity of a Pacific OGCM to the wind stress field used, and Merle and Morlière (1988) have outlined the progress made towards a similar operational model of the Atlantic.

Use of OGCMs of the Indian Ocean has, to date, been very limited. The Meteorological Office model described here is the first one to be used for hindcasting purposes.

3. The model

A 'primitive equation' ocean model is used. This takes the six so-called primitive equations of fluid motion — the x and y components of the momentum equation, the thermodynamic energy equation, the continuity equation, the hydrostatic approximation and the equation of state — and solves them numerically on a finite-difference grid. The numerical scheme is that given by Cox (1984) using the finite-differencing methods of Bryan (1969). The barotropic mode is excluded from the solution. It was thought reasonable to do this since the barotropic velocities in the upper levels (those of interest) are an order of magnitude smaller than the baroclinic velocities. This has the advantage of significantly relaxing the constraints on the time-step used; the time-step for the model grid used here (described below) is 72 minutes, whereas it would need to be about 2 minutes with the barotropic mode.

The complete model domain is from 27° N to 36° S and from 35° E to 125° E. An irregular horizontal grid is used, illustrated in Fig. 2. The maximum latitudinal grid-spacing is 1°; this reduces towards the Equator from 24° N and 24° S, according to a sine function, to be ⅓° within ±1° of the Equator. Longitudinal grid-spacing is 1½° east of 64° E, decreasing westward to be ½° everywhere west of 56° E. The important dynamics of the equatorial and western boundary regions can therefore be relatively well resolved. There are 16 levels in the vertical with a resolution of 10 m for the top 30 m. The model has a constant depth of 4000 m.

The vertical mixing scheme of Pacanowski and Philander (1981) is used, in which the vertical eddy viscosity and eddy diffusivity coefficients depend upon the local Richardson number. The horizontal eddy diffusion coefficient varies across the grid and is set to be proportional to the larger of the latitudinal and longitudinal local grid-spacing. It takes a minimum value of 2×10^7 cm^2 s^{-1}. The coefficients of diffusivity of heat and salinity are constant across the grid, set also at 2×10^7 cm^2 s^{-1}.

The model has closed boundaries except on the southern side. The coast of southern Africa is artificially forced to run due south down the 35° E meridian. The open boundary conditions applied on the southern boundary are designed to keep the vertical profiles of temperature and salinity close to climatology (the climatological fields used are those given by Levitus (1982)).

For these and other model details, including stability considerations, see Gordon (1985).

4. Seasonal-cycle experiment

An experiment was performed with the model in order to simulate the climatological seasonal cycle of currents in the Indian Ocean.

4.1 Experiment details

Climatological forcing fields were used. The applied heat flux is based on a Haney (1971) condition:
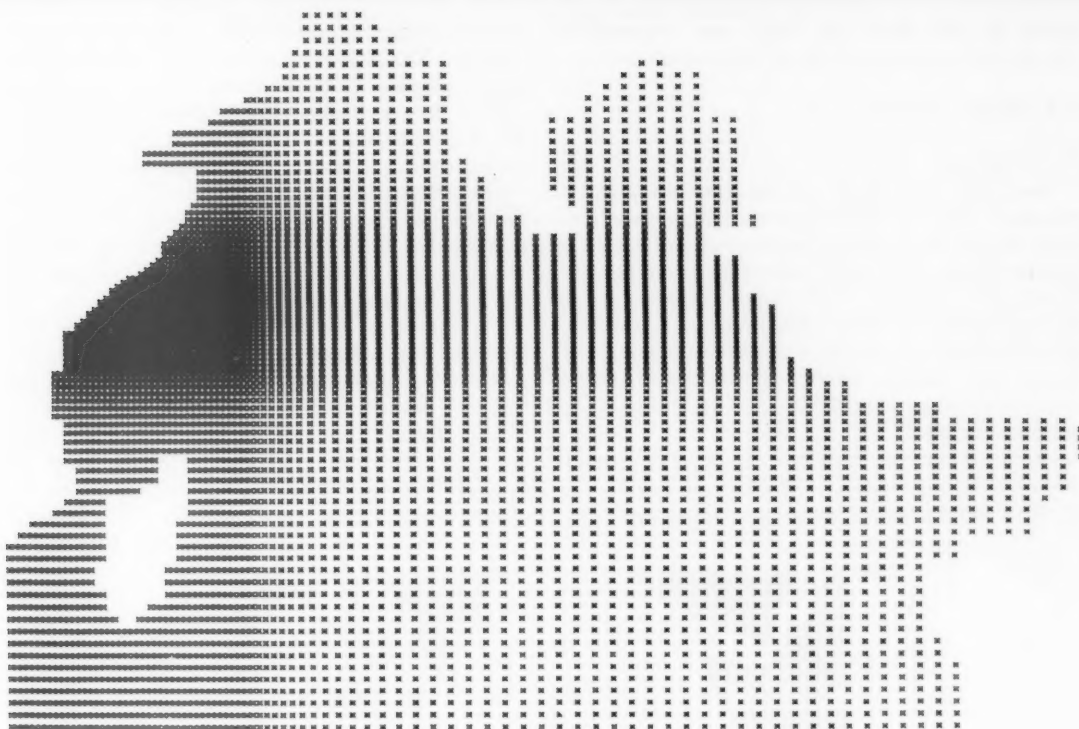
Figure 2. The Indian Ocean model horizontal grid.

$$Q = Q_C + \lambda_H (T - T_C)$$

where

Q = net heat flux
Q_C = climatological net heat flux
T = temperature at the 5 m level (the uppermost grid-point)
T_C = climatological SST
λ_H = Haney heat flux coefficient = $-35 \ \text{W m}^{-2} \ \text{K}^{-1}$.

There is therefore a negative feedback acting on the SST, pulling it towards climatology. Note that when $T = T_C$ the heat flux is equal to the climatological value. The net surface heat flux climatology is taken from Esbensen and Kushnir (1981) and the SST climatology is from the Meteorological Office (Bottomley *et al.* 1990).

The salinity flux is of similar form and depends on the net difference between precipitation (P) and evaporation (E).

$$P - E = (P_C - E_C) + \lambda_S (S - S_C)$$

where

S = the salinity at the uppermost grid point
λ_S = 2 mm(day)$^{-1}$ (ppt)$^{-1}$.

The value of the coefficient, λ_S, is chosen so that relaxation back to the Levitus (1982) climatology occurs on the same time-scale as that of temperature; model experiments have shown that this is necessary for the temperature and salinity fields to evolve in a consistent manner, but there is no specific physical justification for it. The precipitation and evaporation climatologies are taken from Jaegar (1976) and Esbensen and Kushnir (1981) respectively.

For both the heat and salinity fluxes, the magnitude of the feedback term ($\lambda_H(T - T_C)$ and $\lambda_S(S - S_C)$ respectively) indicates the amount of deviation of the model fluxes from the prescribed climatological surface fluxes and is the size of the 'anomalous' flux of heat and fresh water consequently added to or subtracted from the model. These anomalous flux fields may be used as a model diagnostic and will be discussed further in section 4.2.

The applied climatological wind stress is the monthly mean fields given by Hellerman and Rosenstein (1983), who calculated the data on a 2° grid from over 100 years' surface wind observations.

The starting fields used for the experiment were the climatological temperature and salinity fields for September derived from observations by Levitus (1982) and zero velocities. The model was run for just over three years. After a two-year spin-up period, by which time the model had settled to the applied fluxes to a

depth of 200–300 m, the final year (November–October) was taken to represent the seasonal cycle.

4.2 Model results

4.2.1 Currents

The model simulation of the seasonal cycle is compared with estimates of current climatology from observations. The current climatologies used are those given by Hastenrath (1985) (taken from Düing (1970)), Knox and Anderson (1985) (taken from Deutsches Hydrographisches Institut (1960)) and an analysis by Rao et al. (1989) of the ship-drift data set produced by Cutler and Swallow (1984); the observed surface currents for January and July taken from Rao et al. are illustrated in Fig. 3.

The aim of the present study is to simulate the wind-driven circulation and SSTs. The focus of attention is therefore on the upper-level currents, the currents at the uppermost velocity grid-point (5 m) being used for this purpose. Monthly mean currents are presented; this facilitates easy comparison with data from other sources. Because the model SSTs are strongly influenced by the SST climatology used in the heat flux parametrization scheme, they will not be discussed here.

The principal features of the Indian Ocean circulation are well reproduced by the model in response to forcing by seasonally varying climatological winds. Fig. 4 shows the simulated surface currents for three months — January, July and May.

The equatorial surface currents compare well with observations. In January, the NEC, extending to just south of the Equator, and the strong ECC can be seen in Fig. 4(a). Maximum current velocities are realistic: in excess of 60 cm s^{-1} for the NEC, around 40 cm s^{-1} for the ECC, and 20–30 cm s^{-1} for the SEC. The latitudinal positions of these currents are also consistent with observations. In July (see Fig. 4(b)), the maximum
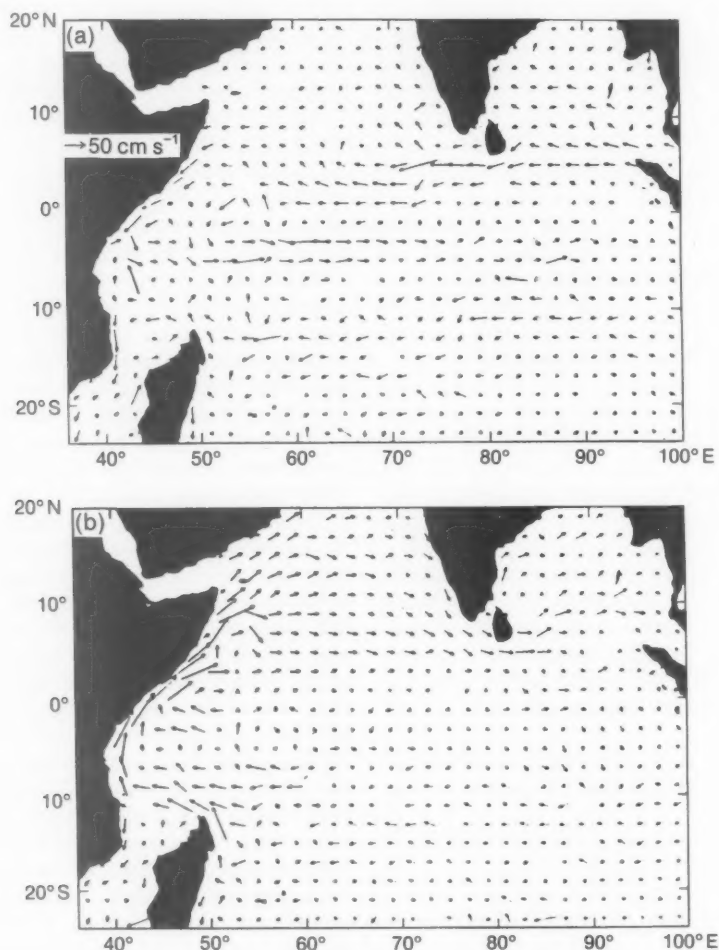
Figure 3. Observed mean monthly ship-drift currents for (a) January and (b) July from analysis by Rao et al. (1989) of ship-drift climatology of Cutler and Swallow (1984).
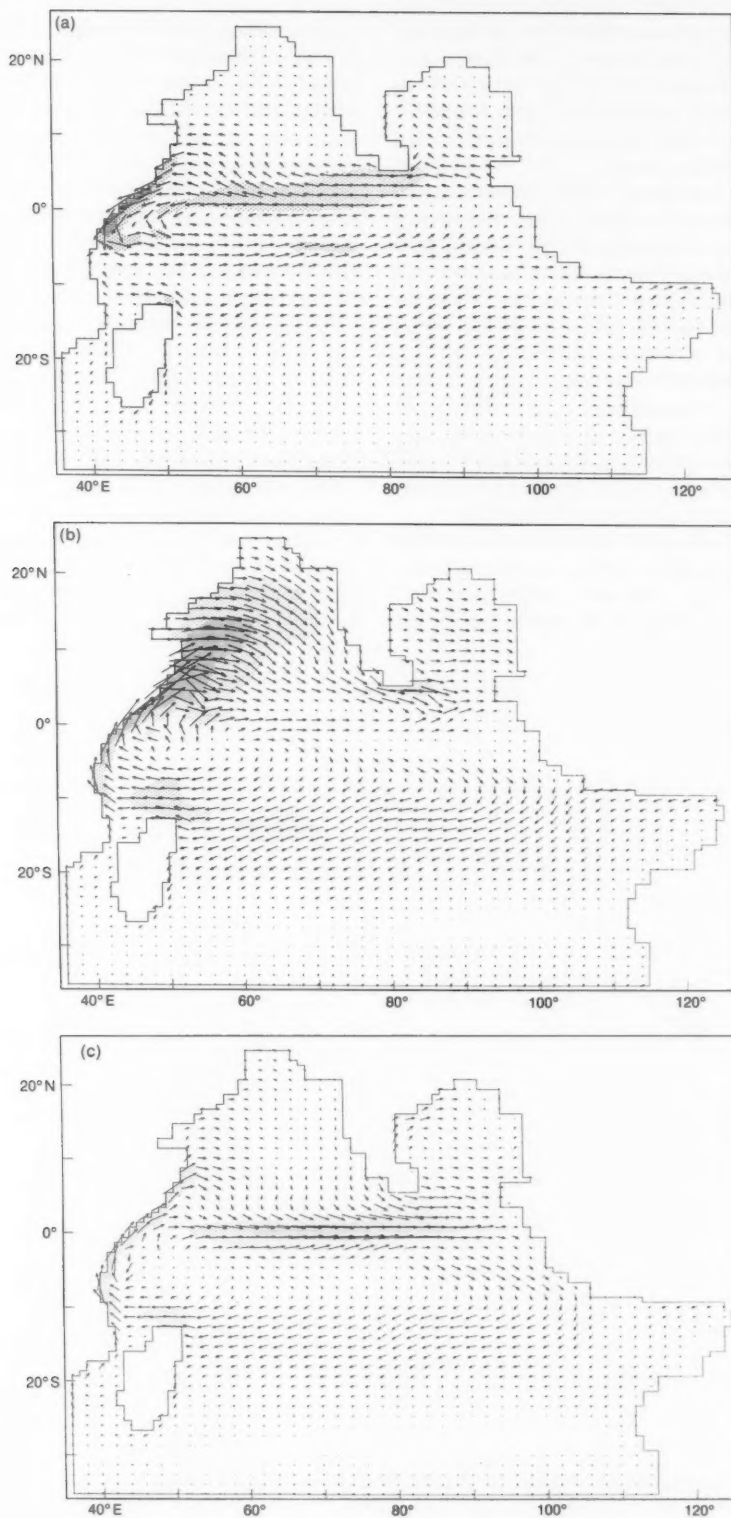
Figure 4. Model seasonal cycle — 5 m currents for (a) January, (b) July and (c) May. Light shading 40–80 cm s^{-1}, heavy shading > 80 cm s^{-1}.

velocity in the SMC of over 80 cm s^{-1} is perhaps too strong, but the weaker flow in the SEC, situated well to the south of the Equator at around 10°S, is well simulated. In both May and September the Wyrtki Jet reaches a maximum velocity of 100 cm s^{-1} (see Fig. 4(c)) which compares well with observations.

In the region of the Somali Current, the seasonal reversal in direction of the flow along the western equatorial boundary is reproduced. Northward flow from where the SEC meets the African coast, across the Equator and into the Somali Current can be seen in Fig. 4(b); a velocity maximum in the Somali Current in excess of 100 cm s^{-1} is reasonable. However, two weaknesses in the circulation are that the recirculation associated with the 'Great Whirl' is obscured in the uppermost model levels (see below), and the model fails to reproduce the Socotra Eddy at all, possibly because the island of Socotra is not represented and the model resolution is lower at that latitude and longitude.

The tendency of the model to obscure the Great Whirl in the upper levels highlights a general model weakness, namely that the Ekman component of the simulated surface currents is too strong. In the case of the Somali

Current, where the wind stress is towards the north-east, the Ekman current is in an eastward direction; the recirculation, which involves westward flow, is not reproduced. At lower model levels, however, the gyre is simulated; this is illustrated in Fig. 5 which shows the currents at 35 m for July. The problem seems to be related to the way in which the downward transfer of momentum from the wind stress is parametrized in the model, but it is not well understood and attempts to eliminate the problem by using other methods to apply the wind stress have been unsuccessful.

In a qualitative sense the principal aspects of the sub-surface currents in the equatorial region are well reproduced, though lack of data makes quantitative comparison difficult. Fig. 6 shows a depth–time plot of zonal velocity at 73°E on the Equator. There is a marked semi-annual cycle in the ECC, as would be expected.

The model simulation of the currents in the deep ocean is not reliable for three reasons. Firstly, there is no barotropic component to the flow, so the deep currents in the model must balance the baroclinic velocities in the upper levels, which, in general, is unrealistic. Secondly, the model spin-up time for the deep ocean is far greater
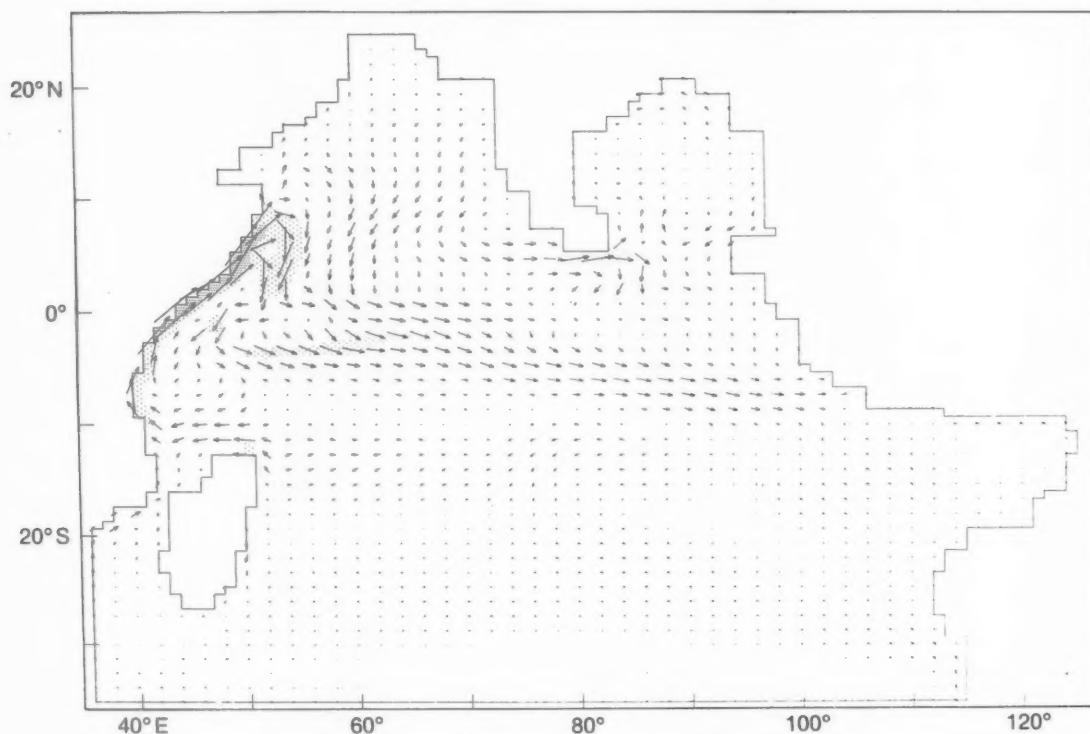
Figure 5. Model seasonal cycle — 35 m currents for July. Shading as in Fig. 4.

than that for the upper layer and so the density distribution will not have reached equilibrium. Thirdly, the model ocean has a flat bottom and does not represent bottom topography. No analysis will therefore be made of the deep currents.

4.2.2 Anomalous heat and water fluxes

The fields of anomalous fluxes of heat and fresh water are indicators, as described above, of the deviation of the model from the prescribed surface climatological fluxes. This deviation can result from inaccuracies in one or all of the following quantities: the climatological fluxes of heat and fresh water; the climatological SST and surface salinity fields to which the model surface

fields are being forced; and the model simulation of surface temperature and salinity.

The anomalous heat flux over most of the model domain is found to be generally in the range 0 to -35 W m^{-2}, which is equivalent to the SST being too warm by 0 to 1 °C. These anomalies are as likely to be a result of inaccuracies in the climatological fields as in the model simulations. The only instances of large anomalous heat fluxes (of magnitude much greater than 35 W m^{-2}) are in areas of strong upwelling, where the model SSTs are significantly cooler than the climatological SSTs; this is illustrated in Fig. 7 which shows the anomalous heat flux for July in which the upwelling along the Somali coast during the South-west Monsoon may be
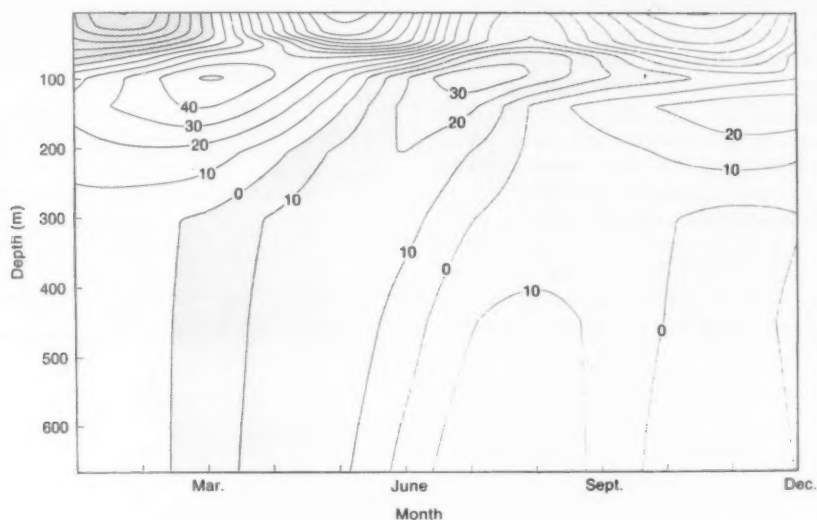

Figure 6.   Model seasonal cycle — depth–time plot of zonal velocity (cm s^{-1}) at 73° E on the Equator (westward values shaded).
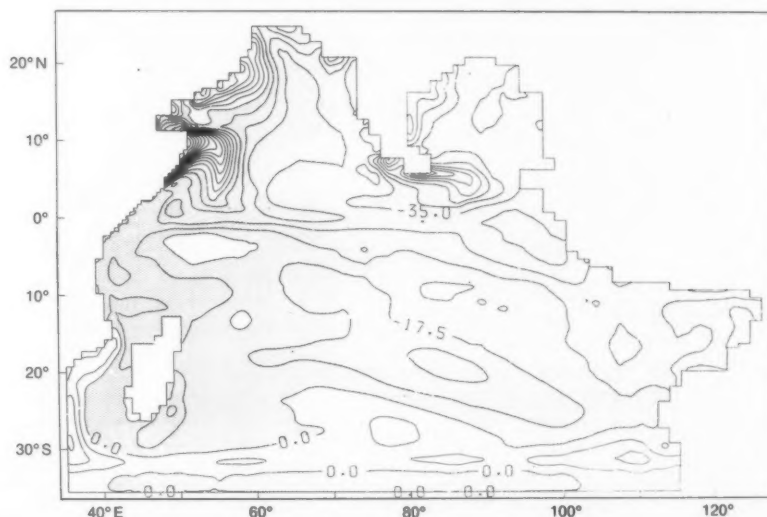

Figure 7.   Model seasonal cycle — anomalous heat flux (W m^{-2}) for July. Positive values correspond to downward heat flux. Contour interval 17.5 W m^{-2} and negative values shaded.

clearly seen. The main reason for the large anomalous fluxes here is that the climatological fields do not resolve the coastal upwelling regions.

The anomalous water flux principally indicates inconsistencies between the flux of precipitation-minus-evaporation $(P-E)$ and the climatological surface salinity field. This is most apparent in the Bay of Bengal since the land surface runoff associated with the Ganges River is not included in the $(P-E)$ climatology; Fig. 8 shows the anomalous water flux for July.

5. Conclusions

An Ocean General Circulation Model of the Indian Ocean has been developed with a view to being able to hindcast the upper-level circulation.

When forced by climatological winds and heat fluxes the model reproduces well the seasonal cycle of the principal surface currents, the only major weakness being in the Somali region. This ability of the model to simulate successfully the seasonal cycle gives confidence in its suitability as a tool for proceeding to an investigation of the interannual variability in the currents in the Indian Ocean in response to actual winds and heat fluxes. For this purpose forcing fields derived from the operational Numerical Weather Prediction model analyses of the Meteorological Office and the European Centre will be used. This will be discussed in a subsequent paper.

Acknowledgements

References

Bottomley, M., Folland, C.K., Hsuing, J., Newel, E. and Parker, D.E., 1990: Global Ocean Surface Temperature Atlas (GOSTA). A joint project of the Meteorological Office and Dept. of Earth, Atmospheric and Planetary Sciences, Masachusetts Institute of Technology.

Bryan, K., 1969: A numerical method for the study of the circulation of the world ocean. *J Comput Phys*, **4**, 347–376.

Cadet, D.L. and Diehl, B.C., 1984: Inter-annual variability of surface fields over the Indian Ocean in recent decades. *Mon Weather Rev*, **112**, 1921–1935.

Cox, M.D., 1984: A primitive equation, 3-dimensional model of the ocean. GFDL Ocean Group Technical Report No. 1, GFDL/NOAA, Princeton, N.J.

Cutler, A.N. and Swallow, J.C., 1984: Surface currents of the Indian Ocean (to 25°S, 100°E): compiled from historical data archived by the Meteorological Office, Bracknell, UK. I.O.S., Wormley, UK, Report No. 187.

Deutsches Hydrographisches Institut, 1960: Monatskarten für den Indischen Ocean, Publ. No. 2422.

Düing, W., 1970: The monsoon regime of the Indian Ocean. International Indian Ocean Experiment, Oceanographic Monograph No. 1. Honolulu, University Press of Hawaii.

Esbensen, S.K. and Kushnir, Y., 1981: The heat budget of the global ocean: An atlas based on estimates from surface marine observations. Report No. 29, Climate Research Institute, Oregon State University, Corvallis.
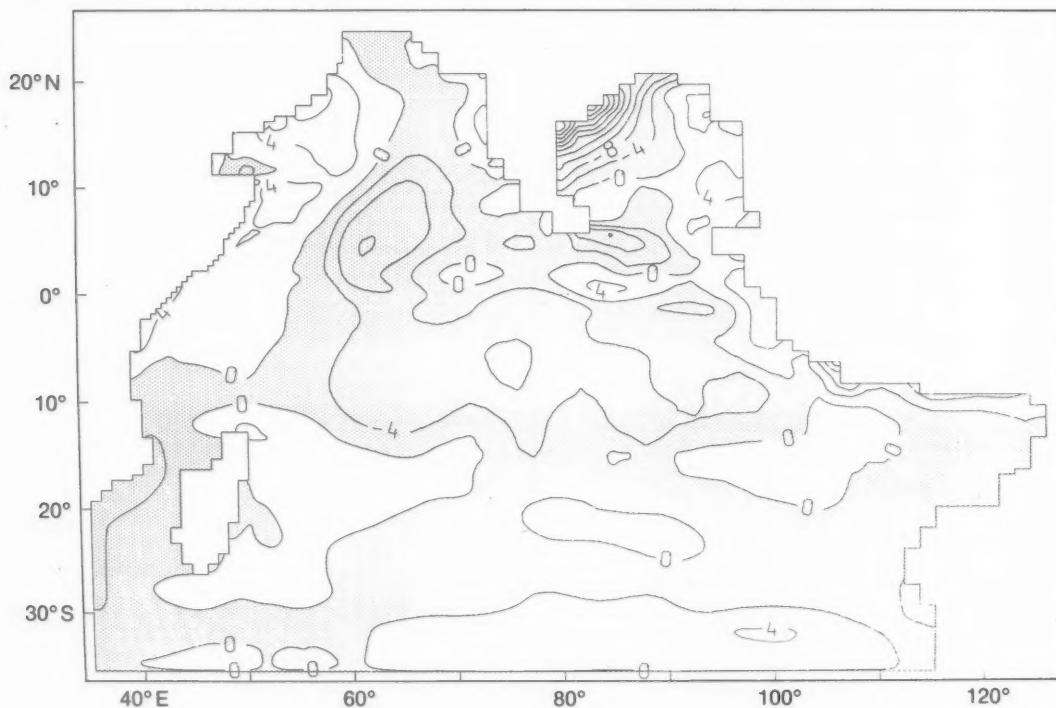

Figure 8. Model seasonal cycle — anomalous fresh water flux (mm(day)$^{-1}$) for July. Negative values correspond to downward fresh water flux. Contour interval 4 mm(day)$^{-1}$ and negative values shaded.

Findlay, A.G., 1866: A directory for the navigation of the Indian Ocean. London, Richard Holmes Laurie.

Gordon, C., 1985: The tropical Pacific version of Cox's ocean model on the Met. Office Cyber 205. Unpublished.

Haney, R.L., 1971: Surface thermal boundary conditions for ocean models. *J Phys Oceanogr*, **1**, 241–248.

Harrison, D.E., Kessler, W.S. and Giese, B.S., 1989: Ocean circulation model hindcasts of the 1982–83 El Niño: thermal variability along the ship-of-opportunity tracks. *J Phys Oceanogr*, **19**, 397–418.

Hastenrath, S., 1985: Ocean circulation. *In* Climate and circulation of the tropics. Dordrecht, Reidel.

Hastenrath, S. and Lamb, P.J., 1980: On the heat budget of hydrosphere and atmosphere in the Indian Ocean. *J Phys Oceanogr*, **10**, 694–708.

Hellerman, S. and Rosenstein, M., 1983: Normal monthly wind stress over the world ocean with error estimates. *J Phys Oceanogr*, **13**, 1093–1104.

Jaegar, L., 1976: Monthly maps of precipitation for the whole world ocean. Offenbach, Deutscher Wetterdienst, Ber. 18, Nr. 139.

Knox, R.A., 1976: On a long series of measurements of Indian Ocean equatorial currents near Addu Atoll. *Deep Sea Res*, **23**, 211–221.

Knox, R.A. and Anderson, D.L.T., 1985: Recent advances in the study of low-latitude ocean circulation. *Prog Oceanogr*, **14**, 259–317.

Leetmaa, A., 1973: The response of the Somali Current at 2°S to the South-west monsoon of 1971. *Deep Sea Res*, **20**, 397–400.

Leetmaa, A. and Ji, M., 1988: Operational hindcasting of the tropical Pacific. *Dyn Atmos Oceans*, **13**, 465–490.

Levitus, S., 1982: Climatological atlas of the world ocean. Washington, NOAA Prof. Paper No. 13.

Lighthill, M.J., 1969: Dynamic response of the Indian Ocean to onset of the South-west monsoon. *Phil Trans R Soc London*, **A265**, 45–92.

Luther, M.E. and O'Brien, J.J., 1989: Modelling the variability in the Somali Current. *In* Nihoul, J.C.J. and Jamart, B.M. (eds); Mesoscale/Synoptic coherent structures in geophysical turbulence, Amsterdam, Elsevier.

McCreary, J.P., Jun and Kundu, P.K., 1988: A numerical investigation of the Somali Current during the South-west Monsoon. *J Mar Res*, **46**, 25–58.

Merle, J. and Morlière, A., 1988: Toward an operational 3-dimensional simulation of the tropical Atlantic Ocean. *Geophys Res Let*, **15**, 653–656.

Pacanowski, R.C. and Philander, S.G.H., 1981: Parametrization of vertical mixing in numerical models of tropical oceans. *J Phys Oceanogr*, **11**, 1443–1451.

Philander, S.G.H. and Seigel, A.D., 1985: Simulation of El Niño of 1982–1983. *In* Nihoul, J.C.J. (ed); Coupled ocean–atmosphere models. Amsterdam, Elsevier.

Rao, R.R., Molinari, R.L. and Festa, J.F., 1989: Evolution of the climatological near-surface thermal structure of the tropical Indian Ocean. 1. Description of mean monthly mixed layer depth, and sea surface temperature, surface current, and surface meteorological fields. *J Geophys Res*, **94C**, 10,801–10,815.

Schott, F., Fieux, M., Kindle, J., Swallow, J. and Zantopp, R., 1988: The boundary currents east and north of Madagascar, 2, direct measurements and model comparisons. *J Geophys Res*, **93C**, 4963–4974.

Schott, F. and Quadfasel, D.R., 1982: Variability of the Somali current system during the onset of the South-west Monsoon, 1979. *J Phys Oceanogr*, **12**, 1343–1357.

Semtner, A.J., 1974: An oceanic general circulation model with bottom topography. Numerical Simulation of Weather and Climate, Tech. Report No. 9, Department of Meteorology, UCLA.

WCRP, 1985: Scientific plan for the tropical ocean and global atmosphere programme. WCRP publications series No. 3, September 1985. Geneva, WMO/TD No. 64.

Wunsch, C., 1977: Response of an equatorial ocean to a periodic monsoon. *J Phys Oceanogr*, **7**, 497–511.

Wyrtki, K., 1973: An equatorial jet in the Indian Ocean. *Science*, **181**, 262–264.

Products and services offered to the agricultural industry by the Meteorological Office*

J.R. Starr
Meteorological Office, Bracknell

Summary

The planning and development of meteorological products and services to the agricultural industry is presented in the light of the emerging commercialism within both the Ministry of Agriculture's Advisory Service and the Meteorological Office itself. Products and services are discussed in terms of 'customer benefits' and 'profitability'; several cost-benefit studies are presented, drawn from both livestock and cropping sectors. While benefits can be large it is noted that the farming community is only likely to benefit if it takes a long-term view of the subscription services. Market research, and market and costings information systems are seen as vital in the search for profitable markets in the agricultural (and other) sectors.

1. Introduction

Most agricultural operations are weather-sensitive; the Meteorological Office has, for many years, had a programme of research and development aimed at providing timely operational weather information services to the agricultural industry.

These services have been targeted at three groups:
(a) the agrochemical industry,
(b) the Agricultural Development & Advisory Service (ADAS) of the Ministry of Agriculture, Fisheries and Food (MAFF), and
(c) the individual farmer or co-operative of farmers.

A close liaison developed with ADAS such that, by 1983, small groups of agricultural meteorologists were attached to each of the five ADAS Regions in England and Wales. Through this link the farming community was served directly, often by on-farm visits (although farmers continued to use forecasts issued by Weather Centres through the usual channels of TV, radio, the Telephone Information Service and, for a time, through the Viewdata system 'Prestel').

There was always a recognition of the need to be accountable for Met. Office resources and some cost-benefit studies were attempted (e.g. the value in carrying out a 'frost survey' of a locality before attempting to establish a frost-sensitive horticultural crop (Rumney 1986)).

2. Commercial pressures

It was in 1987 that ADAS was encouraged, by Government policy, to adopt a firm commercial stance, which resulted in an emphasis on tactical (rather than strategic) revenue-earning services. In response to cuts in funding, the ADAS agro-met. presence was reduced to one 3-man unit based in the West Midlands.

A positive response to these ADAS cuts in funding, however, has been to increase the 'interface' within ADAS, colleges, universities, agrochemical companies, contractors, co-operatives, consultants, with the farming press and overseas international units. These contacts have increased industry awareness of the presence of agricultural meteorology and have resulted in significant increases in revenue; CEC (Commission of the European Communities) contracts have also been sought (e.g. Hough 1990).

In April 1990, the Met. Office was granted 'Agency Status' by its parent ministry, which implied greater flexibility in the allocation of financial and manpower resources, and the setting of realistic (but strict) revenue targets.

In recent years, therefore, it has become vital for the Agricultural Sector to demonstrate that it is an important and cost-effective component of both ADAS and the Met. Office Commercial Services.

3. Services to the customer

3.1 Business plans

Thus it has been that, in anticipation of this commercialism within ADAS and the Met. Office, Agricultural Business Plans have been developed. The stated Aim of the Agricultural Market Sector is 'to lead the productive application of meteorology to agriculture, particularly but not exclusively in the UK'.

The mechanism through which that Aim is realized requires five key components:
(a) an effective interface with the agricultural industry,
(b) an active and relevant R & D programme,
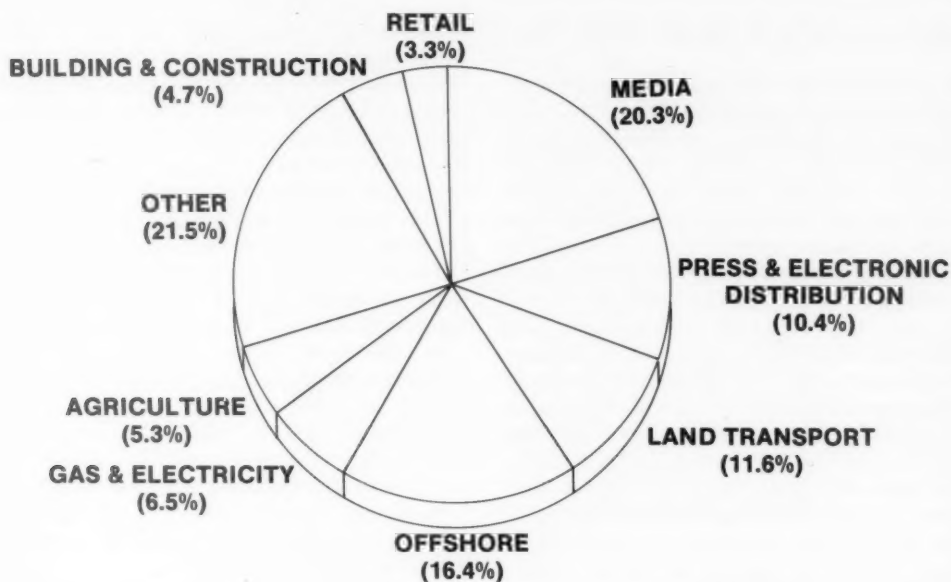(c) a portfolio of services which cater for industry needs and which are commercially viable,

---

Figure 1. Major Markets — the Agricultural Sector share 1989/90.

(d) an appropriate and sustainable mix of staff skills and numbers, and

(e) a rational and up-to-date strategy.

In 1989/90 the Agricultural Market Sector contributed 5.3% of the total £12 million revenue from Commerce and Industry (Fig.1). By 1995/96 it is planned to increase this revenue to £19M in real terms with at least a proportional rise in the contribution from Agriculture (Fig. 2).

3.2 Costs

While the need for commercially viable services has been appreciated for many years, attention has been focused on revenue alone, rather than the revenue in relation to the true costs of the service. These include not only the direct costs of production including staff time, distribution, etc. but also hidden 'core' costs incurred by every National Meteorological Service such as those inherent in maintaining and developing the observational network.

To identify these true costs for every Market Sector, a Financial and Management Information System (FAMIS) is coming on-line.

Contributions towards 'core' costs' amount to 'profit'; the Met. Office is now aiming to market services that result in profitability rather than simply 'revenue'.

3.3 Benefits

The challenge of pricing Services at an acceptable level in the face of strong competition and with these considerable overheads has led the Meteorological Office to produce detailed Marketing Plans in which the Benefits of its Services to the customer are emphasized.
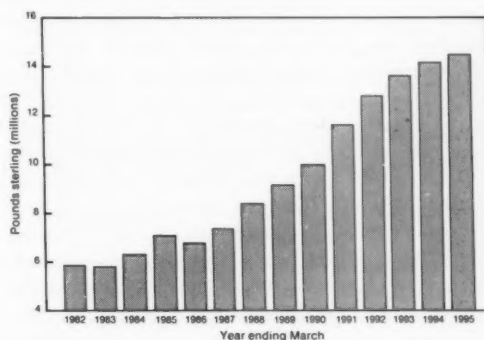

Figure 2. Commercial Service Revenues — actual to 1989, projected to 1995.

These are seen as:
- cost savings
- safety
- improved commercial advantage (competitive edge)
- improved planning
- improved decision-making

The 'brand' name of 'The Met. Office', equated with quality, excellence and reliability, is seen as synonymous with these Benefits.

3.4 Products and Services

Products, then, are being developed, after detailed market research, that are market-led with Customer Benefits as the arbiter. At the same time, developments in Information Technology have meant that high-quality products, tailored to customer needs, can be

delivered so as to allow the customer to take timely action.

A list of Products and Services developed for the Agricultural Industry is given in the Appendix.

To serve the individual farmer, co-operatives and the agrochemical industry, a Market Sector Manager operates from a Weather Centre developing tailored operational services with a substantial forecasting element for targeted customers.

Of crucial importance is the establishing and care of 'Key Clients' by the Market Sector Manager.

4. Costing the benefits

Market research indicates that customers perceive agrometeorological products and services as bringing qualitative benefits, for example as aids to management decisions, but that they have difficulty, even in a controlled trial, in quantifying these benefits. There follow some examples of where it has been possible to do this.

4.1 Foot-and-mouth disease

A numerical model to predict the spread of foot-and-mouth disease is described by Gloster (1983). The disease is not endemic in the United Kingdom; outbreaks are rare, but when they do occur the government maintains a slaughter and compensation policy. During the major epidemic of 1967/68 over 400 000 animals were destroyed and £27M paid in compensation. Estimates of total cost have reached up to £150M (1967/68 prices). Clearly, outbreaks have imposed a severe financial strain on the livestock industry in the United Kingdom.

When an outbreak occurred in cattle on the Isle of Wight in 1983 model output, in the form of daily inhaled virus dosage for cattle within a 10 km radius of the source, was used by the MAFF as an aid to: targeting the risk area for secondary outbreaks, recognizing the relative importance of the airborne route for disease spread, defining areas beyond which markets could continue, etc. In the event, the model indicated meteorological conditions not to be conducive for spread of the virus beyond the island and indeed no secondary outbreaks occurred.

The minimal cost (the order of £100 000) incurred during the outbreak confirmed to MAFF the value of meteorological input in rationalizing the targeting of scarce veterinary resources. The model has now become an integral feature of the guidance resources available to the MAFF epidemiological control team and is also in use in other countries.

4.2 Lamb wind-chill

Starr (1981) reports on trials of a lamb wind-chill forecast trial in southern England. Critical values of a 24-hour wind-chill index likely to result in losses in young lambs were deduced after extensive field trials over several seasons. The forecast trials were run with the co-operation of a number of Berkshire farmers who daily telephoned in to a Weather Centre to be briefed on the forecast chill-factor; particularly important was the 12-hour night-time factor. Farmers saw the benefit in aiding management decisions as to whether to put out the lambs (which were born in-house) or to extend their stay for an extra period under cover.

Thus a severe wind-chill forecast on 21 March 1981 was responded to by a co-operating farmer by retaining all his lambs 'in-house'; 43 lambs died overnight on a neighbouring farm! Under more moderate conditions single and twin lambs might be put out and, for a low index, the triplets — the more sheltered fields being allocated to these weakling stock.

Lamb losses are significant even in lowland Great Britain (about 5%) so benefits of such a service are clear; however the number of farmers taking up the service has been low even though the price represents the market value of only 3 or 4 fat lambs!

4.3 T-Sums*

Daly (1986) reports on an upland grazing trial to evaluate the profitability of an early lamb enterprise, utilizing grass grown according to the T-Sum 200 method.

Nitrogen was applied to two halves of an upland field in Wales at either the date of T-Sum 200 or in late April (usual for the farm). A second dose was applied about 2½ months later. Welsh halfbred ewes and lambs were stocked at 19 ewes and 30 lambs per hectare from May until September and weighed at monthly intervals.

Lamb liveweight produced came to 757 kg ha^{-1} when grassland was fertilized at T-200 and 621 kg ha^{-1} when fertilized later. The T-200 early June fertilizer also gave a more even pattern of grass growth than the late April/mid-July application.

The net output of lamb per hectare after deducting initial weights at the start of the trial was £718 ha^{-1} from the T-200 half and £612 ha^{-1} from the later fertilized half, leading to an overall estimated gross margin of £238 ha^{-1} and £192 ha^{-1} respectively.

4.4 Cutworm

Cost-benefit estimates were made prior to the introduction of an operational cutworm treatment programme for ADAS.

Taking crop area as 170 400 ha, potential loss in high-risk years as £1.098M and corresponding cost of spray treatments as £0.468M, then cost before introduction of the model is estimated as:

---

* Studies in Holland and elsewhere have demonstrated that the optimum response of grass to spring nitrogen occurs when the nitrogen is applied as soon as the average daily temperatures, summed from 1 January (ignoring negative values), reach 200 (°C).

High-risk year:

Crop loss	£1.098M
if 25% of sprays effective	£0.823M
cost of spray	£0.468M
net loss to industry	£1.291M

Low-risk year:

Only 5% of potential loss at risk
and this is saved by treatments.
Net loss is spray cost − value
of crop saved   £0.468M − £0.055M
      = £0.413M

Average cost (mean of low/high figures) = £0.852M

After introduction of the model:

High-risk year:

Crop loss is only	£0.110M
If 90% of sprays effective spray cost	£0.468M
net loss	£0.578M

Low-risk year:

Ability to identify the situation saves 90% of sprays	£0.047M
5% still at risk of which 10% not effectively treated	£0.001M
net loss	£0.048M

Average cost   = £0.313M

Costs to ADAS:

including staff field-intelligence travel	£8 400
Agromet. support at Met. Office costs to ADAS	£1 500
3-day forecasts from a Weather Centre	£2 600
Total cost to ADAS for cutworm service	= £12 500

This contrasts with a potential saving to the industry of £0.54M.

4.5 Forecasts especially designed (tailored) for arable farmers

A market trial was establish with Loddon Farmers, an arable farmer's co-operative in north-east Norfolk (Marketing Solutions 1989). In market research undertaken beforehand, weather information needs were established and a trial forecast service matched as nearly as possible to the identified needs:

(a) Detailed forecasts comprising rainfall, wind speed and direction, sunshine, temperature, sea-breezes, relative humidity and 2-, 3- and 4/5-day outlooks, plus seasonally extra elements such as Smith Period and potential evaporation figures. Forecasts were issued at 0600 with updates at 1200 and 1830.

(b) The forecast was localized to north-east Norfolk, with coastal corrections for the benefit of farmers near the coast. It was competitively priced for the trial at £100.

(c) The service was exclusive to Loddon Farmers of whom 22 initially took up the service. It was delivered by a recorded telephone message on an ex-directory number.

The trial ran for the 6 months May–October 1988. During the trial selected farmers were interviewed and all were interviewed at the end of the trial, the interviews concentrating on the perceived (observed) benefits. The farmers were frequent and regular users of the service; average calls per day varied from 12.8 to 18.7, maximum use being during the harvest and in May when spray applications were frequent. Fifty-four per cent of the calls were in the morning.

Perceived benefits were:

(a) easier planning and decision making; especially useful was the 4/5-day forecast,

(b) greater accuracy and confidence in activities, enabling the day's activities to be 'fine-tuned',

(c) time and cost savings, e.g. overtime planning; less spray wastage; less time on jobs which would have been spoilt due to inclement weather,

(d) convenience of access to forecast, and

(e) other specific benefits mentioned: potential evaporation and soil moisture information for irrigation guidance; Smith Periods as guide to requirement as to when to spay against potato blight; grain-drying need indicated by relative humidity.

All the trialists expressed satisfaction with the service, most spoke of the qualitative benefits (Miller 1990). The service had become integrated into their daily management decisions with the result that few farmers were able to point categorically to savings specifically due to weather information.

Despite this, example of cost savings were quoted by two of the group:

(a) A saving of £9 ha^{-1} in sprays was identified as a consequence of being able to spray with a cheaper spray at the right time. If 40 hectares are sprayed in a day the saving is £360; with 150 farmers making a similar saving on at least one day a year the saving amounts to £54 000.

(b) Cutting a hay crop just before rain can result in losses of £2 000 to £3 000 due to spoilage. One farmer was sure that, through the service, he had avoided such a loss. Thus a co-operative of 100 farmers could save up to £300 000 by cutting only when dry weather is forecast.

The trial allowed re-evaluation of the product, for example inclusion of dew formation and sunshine intensity information, and the proposal of pricing options.

Savings for farmers taking a repayment service are likely to be marginal in the short term compared with

using freely available forecasts or even local knowledge, as noted by Grant (1990). Those who are prepared to go through a learning curve of how best to apply forecast information and use confidence probabilities are the ones likely to achieve long-term benefits.

5. Summary

The commercial culture of the Meteorological Office demands market-led services and products which bring customer-benefits and are profitable. To achieve the correct marketing mix requires careful attention to market research, study of market penetration and being prepared to abandon lines that, however popular, are not profitable.

In developing new agrometeorological products and services there is a need to react to changing farming and ADAS policy, and to capitalize on the current demands for environmental protection, strategies for climate change and the increasing market opportunities overseas (where collaborative agreements with other National Meteorological Services are being sought).

The market among horticultural and farming co-operatives and the agrochemical industry has great potential while the 'Futures' market is a relatively untapped source of revenue.

Market research and the building of a marketing information system by the Meteorological Office Marketing Department will be vital aids to exploring and quantifying the many opportunities in the Agricultural Sector while promotion, marketing and close attention to 'key clients' will continue to be important aspects of the workload of the Market Sector Manager and the Meteorological Office ADAS Unit.

6. Acknowledgements

I am grateful to M. Lee, J. Cochrane, J. Gloster, M. Hough, and B. Callander for supplying examples of cost-benefits and to F. Hayes and M. Nicholls for discussions on the manuscript.

References and bibliography

Daly, M., 1986: T-Sum upland grazing trial. UKF Unpublished Report.
Gloster, J., 1983: Forecasting the airborne spread of foot-and-mouth disease and Newcastle disease. *Philos Trans R Soc London*, **B302**, 535–541.
Grant, M.A., 1990: Operating a semi-commercial meteorological service. Proceedings of the Technical Conference on Economic and Social Benefits of Meteorological and Hydrological Services. Geneva, WMO. Report No. 733.
Hough, M., 1990: Agrometeorological aspects of crops in the UK and Ireland. CEC Joint Research Centre, Catalogue No. CD-NA-13039-EN-C.
Keane, T, Harsmar, P.-O. and Jung, E., 1987: Economic benefits of agrometeorological services. Report No. 27, Commission for Agricultural Meteorology. Geneva, WMO.
Marketing Solutions, 1989: The Met. Office support in the provision of services to the agricultural market — final report.
Miller, I.S., 1990: Benefits of accurate weather forecasting to farmers. *Weather*, **45**, 400–403.
Rumney, R., 1986: A cost/benefit analysis of a spring frost survey. *Agric Mem, Meteorol Off*, No. 1072.
Starr, J.R., 1981: Weather and lamb mortality in a commercial lowland sheep flock. *Agric Meteorol*, **24**, 237–252.

Appendix

Meteorological Products and Services for Agriculture and Forestry (extract from the Meteorological Office's *Commercial Product and Services Manual*, 1991)

Most small businesses will have greatest in the Direct Access Forecaster Service, the Warning Service and Weatherfax. On a very irregular basis they may also express an interest in the Work Days, Growing Days, Irrigation Planning, Climate Suitability and Windbreaks services. Larger companies will express interest in various combinations of products, to make a package. Weatherbase, Work Days, Weather Sensitivity Analysis, Soil Moisture Information and forecast services should always be brought to the attention of large companies, distributors, merchants and manufacturers. Other services should be mentioned as appropriate, examples are:

Heat-Stress Warning — Pig and chicken farmers
Frost Warnings — Fruit growers/Nurseries
Odour-Plume Analysis — Housed livestock
Lamb Wind-Chill — Lowland sheep farmers
Irrigation Planning — Irrigation enquiries
Dedicated services — Co-operatives

A.I. Data Services relevant to feasibility assessment, design, planning or monitoring of a project

World Weather — For different reasons, large growers and importers/exporters of fruit, vegetables and grain need to know what the weather is currently doing abroad and what it will do in the near future.

Weatherbase — Summary data tailored to the needs of the agricultural community — daily, weekly or monthly reports from UK Weather Stations for a variety of crop monitoring purposes.

A.2. Analyses and Consultancies relevant to feasibility assessment, design or planning of a project

Work Days — defines how often a weather dependent task can be done, e.g. crop spraying, autumn cultivations.

Growing Days — relates crop growth to weather to assess the length of growing season for an area, or the time of year (is it longer or shorter than usual?).

Weather Sensitivity Analysis — helps to identify if and/or by how much an activity or demand for produce is weather dependent, e.g. when do consumers switch over to buying salad foods in significant quantities?

Irrigation Planning — an assessment of how much

water can be used in an average, wet or dry season. An objective basis for equipment purchase and licence application. Various rotations can be assessed. The program is designed for UK conditions but limited overseas use (mainly near Continent) is possible.

Climate Suitability — a detailed appraisal to provide the objective basis to answering the question will a crop grow well in a particular location? — United Kingdom and overseas.

Wind-breaks — based on an analysis of wind data, the optimum orientation of a wind-break to protect crops, livestock or buildings can be advised. Wind-breaks can also reduce heat loss. The resultant shading, and light loss can also be assessed.

Depending upon what needs to be protected, protection may only be needed at certain times of the year, e.g. winter for a glasshouse or spring for a delicate crop. In such instances the overall prevailing wind direction may not dictate the best position for the wind-breaks.

Grass Growth — how well is the grass growing in a particular locality compared with average. Useful in forecasting seasonal yields. The program is not sufficiently accurate to model grass-growth in absolute terms but it provides useful information for comparing yields between months and years.

Soil Moisture Information — information can be provided in regular weekly reports for 40 km × 40 km areas for a variety of soil types and crops; the MORECS model. Plus detailed long-period assessments for investigational work and use in Weather Sensitivity Analyses. There is a range of three soil types and over ten crop types.

Accumulated Temperatures — a parameter that is indicative of crop growth and development. Effective day degrees, a similar parameter, can also be calculated.

Return Periods — for a range of meteorological parameters it is possible to provide an indication of how often important extremes will occur, for use in assessing appropriate design tolerances.

Crop, Pest and Disease Indices — the weather conditions liable to encourage a range of pests and diseases have been correlated with outbreaks and indices established. Mostly based on recent past weather but some estimate of future risk can be made particularly if the relationship is temperature dependent.

Odour-Plume Analysis — an assessment of the environmental effects of farm odours given off by housed livestock. It includes information on preferred directions of plume drift on days when odours are likely to remain concentrated at low levels.

Statistics — averages, variability and extremes can be derived from vast archives, the analysis of frost occurrence being a particular case.

Some of the above analyses can be based on overseas data.

A.3. Consultancy-type forecasts

Farmers and growers, as individuals, can be provided with a direct-access forecast service where contact is directly with an experienced forecaster, when required, via an ex-directory telephone contact. The period of the forecast is usually the next 24 hours with outlook up to 5 days ahead.

Forecasts can be provided to agricultural advisory services (government or private) for up to 4 or 5 days ahead as an integral part of their crop and livestock advisory bulletins.

An indication of future trend is possible out to 9 days ahead.

Lamb wind-chill — a customized service aimed at reducing the risk of lamb mortality particularly within first 48 hours of birth and especially if multiple birth. Useful management information for farmers who can take action to protect new-born lowland lambs.

Weather — numerical information sent as a routine (daily) service direct to the customer. Forecast for 5 days ahead and delivered by 7 a.m.

Services to farming co-operatives — dedicated recorded-message forecasting service for co-operatives and associations.

T-Sums — an aid to optimum application of spring nitrogen on grass.

A.4. Warnings of weather events

The customer is contacted by the Met. Office when significant (usually adverse) weather of specific interest is expected. Some examples are:
  Heat stress in intensive poultry and pig units at high temperatures and low wind speeds.
  Strong winds causing structural or crop damage.
  Heavy rain liable to cause flooding.
  Housing and transporting livestock before snow.
  Implementing contingency heating plans prior to very low temperatures.
  Frost on orchards, soft fruit and nursery stock.
  Protection of crops against damage by hail.
  Dry spells for hay and silage making.

Once the critical values are forecast to occur a warning is telephoned or faxed to the recipient, perhaps several days in advance, with daily update until an event has occurred or the danger is passed.

A reassessment of the highest temperature during July 1959

G.P. Northcott
Meteorological Office, Bracknell

Summary

A recent reference to the highest temperature measured in July 1959 has led to a re-examination and reassessment of the previously published value.

1. Introduction

In a recent article in *Weather* (Brugge 1991) the published highest monthly maximum for July 1959, 96 °F (35.5 °C) at Gunby, Lincolnshire, was referred to. Recent examination of the maximum temperatures for July 1959 suggest that the value of 96 °F was perhaps excessive for that location and height particularly when compared to the surrounding stations and notably that at Cottesmore, then Rutland, now Leicestershire, about 4 miles (6 km) to the south and at a similar height above mean sea level (AMSL).

2. Station details

Gunby climate station was situated on the Lincolnshire Wolds, National Grid Reference (NGR) SK 899218, at a height of 440 feet (134 m) AMSL and was open from January to October 1959, after which it ceased to be a climate station, but became a rainfall station, which it remained for three further years.

Some description of the actual site of Gunby is of interest. A photograph of the site shows the screen standing in a field of growing cereal, with no enclosure fence, but with the area immediately surrounding the screen trampled. An inspection was carried out in July 1958, when it was noted that the original screen had single louvres, and the stand was a somewhat unsteady pedestal. However, by early November 1958 the screen had been replaced by a Stevenson screen and the pedestal had been replaced by a stand; there is no indication of an enclosure fence having been erected.

Cottesmore, also situated on the Wolds, NGR SK 909154, at a height of 450 feet (137 m) AMSL, had been a climatological station some years previously, but in 1959 was a synoptic 5-day-week station only and was closed over the weekend. Thus no readings were taken on the Sunday. However, the maximum temperature read at 06 UTC on the Monday morning was the maximum for the weekend. On 6 July 1959 at 06 UTC the maximum was read at Cottesmore as 89 °F (31.7 °C) and the observer noted in the register that the entries for rain and maximum referred to those values for the previous day (Sunday, 5 July).

3. Synoptic situation on 5 July 1959

In the *Monthly Weather Report* for July 1959 (Meteorological Office 1959) the following description is given of the weather over the first week;

'Weak fronts in a moist south-westerly airsteam gave cloudy weather with some slight occasional rain in most districts during the first three days of the month. Meanwhile an anticyclone had been moving eastwards from the Bay of Biscay and as pressure rose over Germany on the 4th, wind over the British Isles became light but mainly southerly and weather sunny and warm generally except in northern Scotland. many places recorded between 14 and 15 hours of sunshine and temperature rose into the eighties in most districts and reached 88 °F at Cromer. On the 5th thunderstorms, associated with an eastward moving weakening upper trough, broke out in western districts and moved slowly across the country reaching south Yorkshire and Lincolnshire during the afternoon. In many midland and eastern districts the 5th was the warmest day of the year, so far, with afternoon temperatures exceeding 90 °F; Gunby recorded 96 °F and Cromer 94 °F.'

The hourly plotted chart for 16 UTC on 5 July (Fig. 1) has a front drawn along a line from just west of the Isles of Scilly to Anglesey to Carlisle and across to the Moray Firth, and a thermal low pressure area, with a central pressure value of 1012.6 mb near Wittering. A large area of Sferics plotted across the top of the shallow low pressure area confirming the thundery outbreaks in 'south Yorkshire and Lincolnshire during the afternoon'.

4. Re-examination of highest temperatures

A map was plotted of the maximum temperatures in southern and eastern England on 5 July 1959 (Fig. 2) using the values published in Table III of the *Monthly Weather Report* (Meteorological Office 1959). Those maxima that occurred on other days did not generally exceed the values on this, the hottest day of the month. The 90 °F isotherm bends a little around Cottesmore
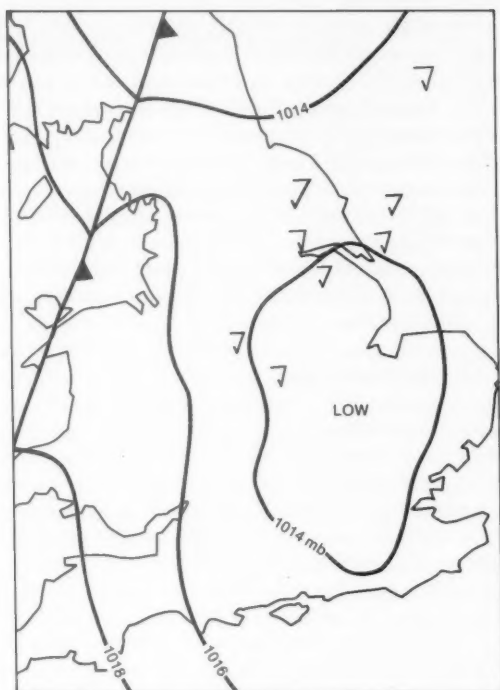
Figure 1. Surface chart for 16 UTC on 5 July 1959, with sferics added.

Figure 2. Map of maximum temperatures in southern and eastern England on 5 July 1959.

with its 89 °F, having passed very close to Gunby, and suggesting that the highest temperature during the day should have been about 90 °F.

An examination of the archived evidence shows that the observer at Gunby measured 81 °F at 09 UTC on the 5th, and on the following morning his reading of the maximum thermometer gave him 96 °F for the previous day. The entry on the return is absolutely clear and the 9 and 6 are quite distinct, with no possibility of confusion with say a zero. However, when read the values are entered into a Climatological Register to make up the observation before it is transcribed on to a Metform 3208 (Monthly Climatological Return). It is possible that an error was made in reading the maximum, or that the maximum temperature was correctly read, but wrongly transcribed on to the Metform 3208 because of problems of legibility at the earlier stage. The earliest 'original' stage kept in the National Meteorological Archives is the Metform 3208. Climatological Registers are not deposited within the Archives.

The maximum temperature on the 5th at Gunby was accepted as the highest temperature for July 1959 only and not as general record-breaker; it is difficult to obtain precise details of the thinking of the Quality Control staff of the period, but the *Observers' Handbook* (Meteorological Office 1956, 1969), referring to gross errors in temperature states 'One of the commonest of such gross errors is the misreading of the thermo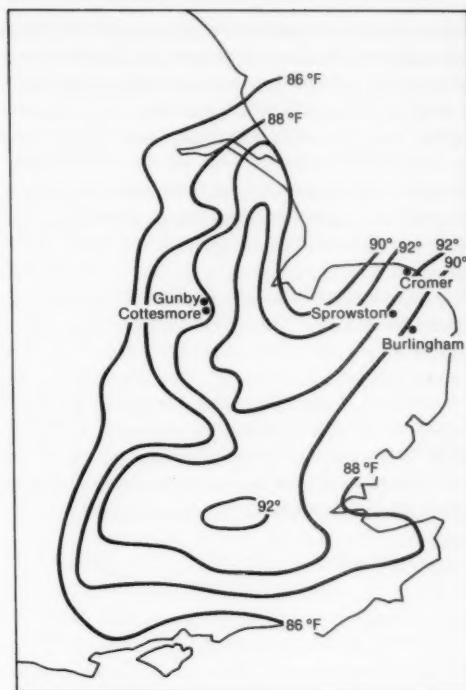meter by 5 or 10 whole degrees ...'. However, there is no evidence that the value recorded on the Metform 3208 was other than that read on the instrument. No evidence has come to light to suggest that the value of 96 °F on 5 July 1959 has previously been queried, let alone investigated. However, it is not the highest value for July in the literature.

5. July extremes

The extreme for July was 38.1 °C, recorded in a Glaisher stand at Tonbridge on the 22nd in 1868, but this value was amended to 35.9 °C recorded in a Stevenson screen at Cheltenham on 3 July 1976, following the discovery that the temperature in a Glaisher stand is generally higher than the temperature in a Stevenson screen (Laing 1977). The extremes given for East Anglia and Lincolnshire in *Climatological Memorandum 133* (Meteorological Office 1984: revised 1989) are 36.1 °C at Halstead, Essex on 19 August 1932 and 35.6 °C at Cambridge Botanic Garden on 9 August 1911 and 19 August 1932 as well as 35.6 °C at Earl's Colne and Norwich on 19 August 1932.

6. The reassessment and statement

The differences in the maxima and minima at Gunby were compared with those for Cottesmore and Wittering over the 2-month period of June and July 1959, and a similar exercise was carried out to compare Cromer with two nearby stations, Sprowston (NGR TG 251123) and Burlingham (NGR TG 373101). For this purpose the

relevant maximum and minimum temperatures were extracted from the Daily Registers for Cottesmore and Wittering. For the other stations examined in this way copies were taken of the relevant Metform 3208 returns for June and July 1959. These data were passed to the Observation Provision Branch of the Meteorological Office for examination by their networks section, who produced the statement reassessing the Gunby value and checking the rather high value read at Cromer on that day.

The full statement on the 'highest daily maximum temperature during July 1959' made by the networks section is as follows:

'Gunby (situated on the Lincolnshire Wolds) reported a maximum temperature of 96 °F on 5 July 1959. This value was recorded as the highest monthly maximum for July 1959, but appears to be unreasonably high in comparison with neighbouring stations:

Station	Altitude (m)	Max. Temp. (°F)
Gunby	134	96
Cottesmore	138	89
Wittering	80	91

Maximum temperatures at Gunby were compared with those from Cottesmore and Wittering for the period from 15 June to 20 July 1959. Values were generally similar except on three days:

Station	Altitude (m)	Maximum temperature (°F)		
		22 June	1 July	5 July
Gunby	134	88	69	96
Cottesmore	138	77	74	89
Wittering	80	79	75	91

There would seem to be little reason why temperatures should differ by these amounts and allowing for the fact that Gunby was only open from January to October 1959 it would therefore be unsafe to accept the value on 5 July as the highest maximum temperature for the month.

The values at Gunby on 22 June, 1 July and 5 July should therefore be changed to 77 °F, 74 °F and 91 °F respectively.

The next highest value was 94 °F, reported at three stations: Westminster (London), Boxworth (Cambridgeshire) and Cromer (Norfolk). The values at the first two stations agree well with those of their neighbouring stations. The value at Cromer seems a little high in comparison with its neighbours:

Station	Altitude (m)	Max. Temp. (°F)
Cromer	54	94
Sprowston	28	89
Burlingham	27	87

A study of maximum temperature values from 15 June to 20 July 1959 showed that Cromer was usually 0–10 °F colder than Sprowston or Burlingham but on some occasions was a few degrees warmer. This is as might be expected for a station close to the North Sea. On 5 July the wind during the early afternoon was from the south-south-east and with the hills to the south of Cromer rising to between 200 and 250 feet a value of 94 °F can be accepted even though a little dubious. There is insufficient evidence to declare that the value of 94 °F is wrong, especially 31 years after the event.'

7. Corrective action
As a result of the reassessment of the values for the month of July 1959 it was clear that the 5th remained the hottest day, but that the information about the corrected highest value should be brought to a wide readership. The following correction appears in the December 1990 and the Summary issues of the *Monthly Weather Report* (Meteorological Office 1991):

'Vol. 76 No. 7, **Temperature**

A recent re-examination of the high temperatures in July 1959 show that it is unsafe to accept the value of 96 °F (35.5 °C) recorded on the 5th at Gunby, Lincolnshire, as the highest of the month. The Metform 3208 in the Archives for Gunby for July 1959 has been annotated accordingly. The next highest value was 94 °F (34.5 °C), reported at three stations: Westminster (London), Boxworth (Cambridgeshire) and Cromer (Norfolk). The value at the first two agree well with their neighbouring stations; the value at Cromer, although it seems a little high, is acceptable...'

Acknowledgements
Thanks are due to Philip Eden whose letter, now published in *Weather*, (October 1991) started the investigation, to Mick Wood, the Archivist for making available the returns and to Eddie Spackman of the Observation Provision Branch for his advice and for a statement based on comparison of the available data.

References
Brugge, R., 1991: The record-breaking heatwave of 1–4 August 1990 over England and Wales. *Weather*, **46**.
Eden, P., 1991: Gunby, Lincs., Putting the Record Straight; Letter in: *Weather*, **46**, 330–331.
Laing, J., 1977: Maximum summer temperatures recorded in Glaisher stands and Stevenson screens. *Meteorol Mag*, **106**, 220–228.
Meteorological Office, 1956: *Observer's Handbook*, 2nd ed., p. 13. London, HMSO.
—, 1959: *Monthly Weather Report*, July 1959, **76**, No. 7, London, HMSO.
—, 1960: *Monthly Weather Report*, Summary 1959, **76**, No. 13. London, HMSO.
—, 1969, *Observer's Handbook*, 3rd ed., p. 12. London, HMSO.
—, 1991: *Monthly Weather Report*, December 1990, **107**, No. 12, p. 291. London, HMSO.
—, 1984, revised 1989: *Climatological Memo Meteorol Off* No. 133, p. 15. London, HMSO.

Notes and news

The Professor Dr Vilho Vaisala Award

Malcolm Kitchen of the Meteorological Office was presented with the prestigious Professor Dr Vilho Vaisala Award by the President of the World Meteorological Organization (WMO), Mr Zou Jingmeng, at the Met. Office HQ at Bracknell on 16 September 1991.

Malcolm helped to organize the WMO Radiosonde Comparison held at the Office's experimental site at Beaufort Park near Bracknell in 1984. The award came for his definitive report comparing the performance of the upper-air stations of the Global Observing Network. If his recommendations are adopted they will lead to a substantial improvement in compatibility of the different instruments and systems used around the world. He acted as the WMO's Commission for Instruments and Methods of Observation Rapporteur on Radiosonde Compatibility from 1985 to 1989.

Before 1984 Malcolm had worked in the Office's Cloud Physics section and the Meteorological Research Flight. He has also been responsible for the operational trials of the ATD lightning detection system. His present interests are in developments to the combined radar and satellite short-period rainfall measuring and forecasting system FRONTIERS.

In presenting the Award, which consists of a diploma and a cheque for US$1,000, Mr Zou, who is also the Administrator of the State Meteorological Administration of China, said:

> 'Mr Kitchen has provided an important contribution to the standardization of upper-air measurements. The presentation of the Vaisala Award to Mr Kitchen is a well-earned recognition of his work for the meteorological community, to which I should like to add the appreciation of WMO for his valuable contribution to meteorological operations and research.'

Reviews

Climate and development: Climate change and variability and the resulting social, economic and technological implications, edited by H.-J. Karpe, D. Otten, S.C. Trinidade. 154 mm × 234 mm, pp. xiv+477, *illus*. Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1990. Price DM. 98.00. ISBN 3 540 51269 1.

This book consists of papers presented at the Hamburg Congress on Climate and Development in November 1988. The Congress was interdisciplinary and attracted 40 contributors from 13 countries, though most delegates were from Germany and the USA. There are 9 introductory addresses, mostly of little interest, 11 scientific contributions, 9 which focus in turn on the concerns of industry, non-governmental organizations (NGOs) and developing countries, and 5 on international programmes in this area. The Congress agreed two statements: a three-page Manifesto and a two-page Action Plan.

It is understandable that a book should emerge from such a conference, though it is a pity that the editors felt they had to include all the material to hand. Beyond the ephemeral material there are some useful summaries of current evidence and predictions of global warming, and the different emphases of the various groups are of some interest. Inevitably there are conflicts in the conclusions reached by the scientists who contributed and these will not be easy to resolve for most readers.

Klaus Hasselmann of the Max-Planck-Institut für Meteorologie in Hamburg provides an excellent well-illustrated 12 000-word summary of the state of the art in climate forecasting. A later contribution by Wilfred Bach goes over too much of the same ground, though he does introduce the distinction between transient and equilibrium response. There is also an interesting paper by Gundolf Kohlmaier on the place of land biosphere changes in the atmospheric CO_2 budget. Given the unbalanced state of current global carbon models, this is an important area deserving further analysis and research and this is one of the most original papers here.

The Russian contribution by Budyko and Sedunov has the title *Anthropogenic Climate Changes*. It runs to over 5000 words, but is rather repetitive and not always easy to read. It has value as a review of Russian research in English, though most of the figures have inadequate captions. The authors seem inclined to regard warming as an improvement on the current Russian winter, a welcome aided by their happy assumption that precipitation will increase whilst they seem to set aside the fact that evapotranspiration will also be greater. The all-important oceans are represented by a single paper which gets no further than describing the various international programmes such as WOCE and TOGA.

Ian (here rendered as Ivan) Burton from Canada puts forward the aim of a rapid reduction in CO_2 output (of over 20% in all developed countries by 2005), a target which few others accept and most regard as impracticable. But even this Canadian target is not enough for the NGO group which asks for a reduction in emissions of at least 30% by 2000 and 60% by 2015, surely pie in the CO_2 sky! It is disconcerting to discover how other actors on the global-change stage can reinterpret these messages. Thus a German author from the coal industry manages to delay CO_2 doubling for 200–300 years, partly on the assumption that there will be major and continuing changes in the efficiency with which we produce our energy from fossil fuel. However, he also manages to improve his scenario by describing doubling in terms of CO_2 alone, neglecting the role of methane, nitrous oxide and the CFCs which contribute, as CO_2 equivalent, to produce the IPCC date of *circa* 2030 for doubling.

The Action Plan put forward at the Congress fully accepts the reality of future global warming and envisages relatively strong international responses in due course. However, there is no agreed target, emphasizing the long way future international negotiations have to go. One of the introductory statements is well worth study in this regard, a perceptive political comment by a member of the German *Bundestag*. His core point is that the threat of future global warming essentially adds a further strong reason why we need to take up such challenges as under-development and resource depletion, yet makes them even more difficult to solve constructively and effectively.

The socio-economic aspects also addressed by the Congress are represented by a number of shorter papers. There are some useful ideas in a rather selective survey of energy options by Roger Revelle and David Burns. The one UK contribution rehearses Martin Parry's views of the impact on agriculture, necessarily limited by the inability to say anything reliable about future precipitation. Michael Glantz of NCAR writes on climatic variability, climatic change and development in sub-Saharan Africa, but the paper says little that is new. Uncertainties over future water balance abound, yet it is not until page 405 that we find J. Nemec of FAO considering the effect of higher E on the future P-E equation.

The last substantial paper is a 7000-word essay by Thomas Potter and Lars Olsson of the World Climate Programme of WMO. It is an overview of international developments, trends and views, which describes what has been done and discusses why progress remains rather slow. It concludes that the fundamental 'renewable natural resources' on which all others depend are climate and water and the goal of any development must be to leave these as 'substantial natural resources'. That summarizes succinctly the aim of most of the authors of this book, but they cannot agree on how to bring it about.

K.M. Clayton

Global environmental change, edited by R.W. Corell and P.A. Anderson. 169 mm × 247 mm, pp. xiv+264, *illus.* Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1991. Price DM158.00. ISBN 0 387 531289.

Autonomous Robotic Warfare? Acoustic Submarine Interception? Thus might one speculate upon encountering the acronyms 'ARW' or 'ASI' in the context of NATO. In fact, they stand for Advanced Research Workshop and Advanced Study Institute, and for those who have not been directly involved in NATO scientific programmes it may come as a surprise to find that they refer to NATO's programme of environmental rather than defence or weapons research.

Global environmental change is the report of a conference designed to assist NATO plan its environmental research programme; in designing this particular 5-year programme of ARWs and ASIs the programme arthitects wished to ensure that the NATO programme was consistent with, and complementary to, existing internationally-organized endeavours. The programme also aims specifically to promote interdisciplinary collaboration. Both of these are laudable aspirations and the conference, which is primarily a review of questions rather than answers, seems to me to represent real progress towards achieving them. The full background to the conference is explained at length in the Preface and in the two chapters of Part 1.

Part 2 surveys the landscape of international activity related to the global environment. For those who don't know your JGOFS from your GEWEX, or — shame on you — thought that a TOGA was something you wore, then prepare to receive your education here. It is unusual, and therefore doubly valuable, to find almost all the major programmes described in the pages of one document. The scientific goals of the individual programmes are described in greater detail in Part 5.

Part 3, probably the most readable, deals with the state of some of the scientific disciplines concerned with the environment, covering hydrology, ecology, biogeochemical modelling (particularly carbon cycle), climate observations and the human dimensions of environmental change. In this latter chapter, the author masked much good material by fulfilling the physical scientist's caricature of social science. Attempting to cover too broad a canvas, he alternated between truisms and imponderables and indulged in unhelpful grandiloquence — why did it have to be 'substantive priorities' rather than plain 'priorities'?

But this was my only real complaint, for the authors of the rest of Part 3 generally made a good job of outlining the status of their discipline and, in the spirit of the workshop, of acknowledging where appropriate its limitations, whether of physical scale ('Ecologists have not until recently concerned themselves with global issues') or of cross-disciplinary collaboration ('hydrology ..(needs).. a willingness to simultaneously consider non-water fluxes').

The chapter on climate observations seems to be more of an excuse for the author to advance his objections to the conclusions of the IPCC Scientific Assessment (that global temperature has increased by 0.5 °C over the last century) than an objective review, but it makes interesting reading.

Part 4 completes the tour of the science with a review of modelling and data needs. The chapter on 'Earth system and astronomical climate modeling' almost attempts too much in covering all length- and time-scales, but in the end settles, somewhat arbitrarily it seems to this reader, on simulation of the last glacial-interglacial cycle.

Overall the book is an excellent, though volatile,

contemporary reference document (it will be obsolete in 3–5 years). Although there is no index, the information is clearly presented and the quality of production is high.

B.A. Callander

Chemistry of atmospheres (second edition), by
R.P. Wayne. 154 mm × 234 mm, pp. xiii+447, *illus.* Oxford, Clarendon Press, 1991. Price £45.00 (hardback), £19.50 (paperback). ISBN 0 19 855571 7, 0 19 855574 1.

This is a revised edition of a book first published in 1985 and has a number of features reflecting the changes in our understanding of atmospheric chemistry since that time. Most important of these is the discovery of the Antarctic ozone hole, which has now been fairly well explained by the scientific community and a clear and accurate account is given by Dr Wayne. There has also been additional material added on extra-terrestrial atmospheres and the book includes a brief summary of the recent IPCC document on climate change. Although these changes are very welcome there are large parts of the book which have undergone little revision despite some possibly substantial changes in our understanding. To avoid these doubts regarding some of the details it would probably have been more useful to the reader if appropriate references had been placed within the text. As it is, many new references are included in the list at the end of each chapter but one is left wondering whether these are properly represented by the comments in the text.

The book starts at a rather basic level, leading the reader gently into the subject. This is on the whole accurate and well written, although I was confused by the remark on p. 21 that 'no geologic evidence exists for large fluctuations of CO_2 in the past'. Once the more advanced material gets under way, Dr Wayne's sometimes over-florid style occasionally gets the better of him such as in the section on models of atmospheric chemistry where we learn (p. 112) that some 'inspired guesswork' is required in the formulation of family models. This section is perhaps a little outdated since the wider availability of supercomputers has meant that the old one-dimensional models have become largely supplanted by two-dimensional models, with an increase in the use of three-dimensional models. The chapter on stratospheric chemistry is generally well presented and clear. Some of the material has not been revised since the early edition. One example of this is the table on p. 138 showing the relative contributions of the various catalytic cycles in destroying ozone. The table is taken from a 1981 compilation when not all the reservoir species were properly established nor their reaction rates known very accurately. Thus one is left wondering whether 1990 reaction rates might provide a different quantitative picture. Nonetheless the essential points are effectively made in that the processes are nonlinear. A number of reactions are also isolated as being 'important'

without proper justification, in my view. The chapter on tropospheric chemistry is extensive. This is a subject of great complexity and Dr Wayne is not entirely successful in clarifying all the relevant processes. The remainder of the book gives a good introduction to the ionosphere and planetary atmospheres, subjects which have been much less extensively investigated. Again there has been a modest amount of new material added from the first edition but the author can perhaps be excused due to lack of space in a book of this size. The final chapter describes the evolution of atmospheres. This might be considered more the domain of astronomy but contains a small part on climate change on the earth.

On the whole I have only minor criticisms of a book that is generally clear, well written and covers a wide ground. Further, the physical processes relevant to particular phenomena are generally well explained. The changes from the first edition are relatively minor so those in possession of the first edition probably wouldn't wish to buy the new edition. For others, whether students in the subject or researchers of longer standing, the book is definitely recommended.

J. Austin

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Impact of climatic variability and change on river flow regimes in the UK, by N.W. Arnell, R.P.C. Brown and N.S. Reynard (Wallingford, Institute of Hydrology, 1990. £12.00) examines the recent past variability of river flow regimes and considers the possible consequences of future climate change. Conclusions are drawn on both investigations, and future research needs are identified. ISBN 0 948540 26 5.

Prediction and regulation of air pollution, by M.E. Berlyand (Dordrecht, Boston, London, Kluwer Academic Publishers, 1991. Dfl.175.00, $108.00, £61.00) presents the scientific and methodological foundations of the subject. Practical recommendations for their implementation in a variety of scenarios are also included. ISBN 0 7923 1000 4.
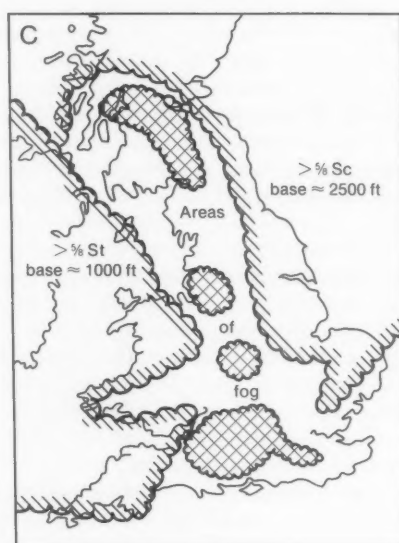
Historic storms of the North Sea, British Isles and Northwest Europe, by H.H. Lamb and K. Fryendahl (Cambridge University Press, 1991. £55.00, $95.00) discusses all the wind storms with serious effects since the Middle Ages. The lead author founded the Climate Research Unit at the University of East Anglia and has been embroiled with the subject for several decades. ISBN 0 521 37522 3.

Satellite photographs — 22 October 1991 at 0428 UTC
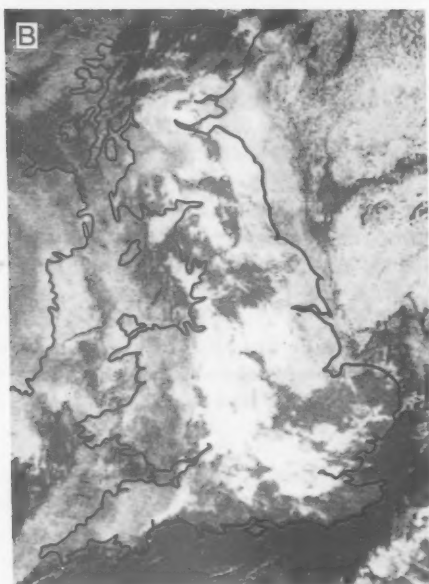
During the day, fog is easily detectable from its bright appearance in the visible and its comparatively warm brightness temperatures. At night, this method is no longer, of course, possible. Conventional infrared images alone are not sufficient; fog often has the same brightness temperature and texture as the underlying surface.

Images intended to show the distribution at night can, however, be produced from two channels (i.e. different wavelengths) of the imaging instrument on the NOAA series of polar orbiting satellites. It turns out that fog/low cloud emits radiation less efficiently at one wavelength than at the other. Land and sea surfaces emit with approximately the same efficiency.

Fog will, therefore, have a different apparent temperature in the two channels, whereas land and sea will have the same. Thus, the difference in the apparent temperatures is indicative of the presence of fog. Images are generated routinely on Autosat-2 from this temperature difference.

Image A shows the UK area at about 0428 UTC on 22 October 1991 in the infrared: the dark areas are relatively warm; the light areas cool.

Image B shows the temperature difference between the two infrared channels. The white areas are where fog and low cloud is present. The black areas (in the north and to the west of Cornwall) are due to cirrus cloud.

'C' shows a simplified representation of the distribution of fog and clouds derived from the observations at 0500 UTC.

The position of the low stratus in the west corresponds to the light grey signature in image B, and the relatively warm cloud tops shown in image A. The stratocumulus in the east and in south-west Britain is also light grey in image B, but image A shows that the cloud tops are relatively cool.

The fog over central Britain correlates well with areas that are both dark (and hence, relatively warm) in image A and bright (and hence, with a relatively large inter-channel temperature difference) in image B. The marked differences between the two images over central England shows the value of the inter-channel temperature difference in determining the position of the fog.

R.J. Allam and G. Holpin

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (Compucorp or IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

Tables should be numbered consecutively using roman numerals and provided with headings.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

Articles for publication and all other communications for the Editor should be addressed to: The Chief Executive, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

Illustrations

Diagrams must be drawn clearly, preferably in ink, and should not contain any unnecessary or irrelevant details. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text. The sequential numbering should correspond with the sequential referrals in the text.

Sharp monochrome photographs on glossy paper are preferred; colour prints are acceptable but the use of colour is at the Editor's discretion.

Copyright

Authors should identify the holder of the copyright for their work when they first submit contributions.

Free copies

Three free copies of the magazine (one for a book review) are provided for authors of articles published in it. Separate offprints for each article are not provided.

Contents

1.0 2.8 2.5
2.2
1.1 2.0
1.8
1.25 1.4 1.6